

SPACE ROBOTICS IN JAPAN

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SUMMARY**Infrastructure and Program**

Japan has been one of the most successful countries in the world in the realm of terrestrial robot applications. The panel found that Japan has in place a broad base of robotics R&D, ranging from components to working systems for manufacturing, construction, and human service industries. From this base, Japan looks to the use of robotics in space applications, and has funded work in space robotics since the mid-1980s. The Japanese are focusing on a clear image of what they hope to achieve through three objectives for the 1990s: developing long-reach manipulation for tending experiments on Space Station Freedom, capturing satellites using a free-flying manipulator, and surveying part of the moon with a mobile robot. This focus and a sound robotics infrastructure is enabling the young Japanese space program to develop relevant systems for extraterrestrial robotics applications.

Space robotics in Japan has involved government agencies, national research laboratories, universities, and companies. The government agencies responsible for space activities are the National Space Development Agency and the Institute of Space and Aeronautical Science, and, to a lesser extent, MITI.

Japanese industry recognizes the future potential of space, and the larger Japanese mechatronics companies engage in space robotics research. The panel found most industry research to be strongly applications-oriented. Government contracts have been let to companies with aerospace and industrial robotics experience; multiple

contractors may take part in a major project. In the U.S., by contrast, one corporation usually acts as the prime integrating contractor. Japanese universities are also involved in space robotics research. Universities provide a stream of basic research contributions, but have played only minor roles in large robotics projects.

Funding for Japanese space robotics research and projects has come from the government, with cost sharing by corporations. Japanese procurement practices appear to have engendered cooperation among Japanese corporations, and companies have rotated contracts. Government contracts tend to be smaller and to make up a smaller proportion of a company's business in Japan than in the U.S. Less funding is apparently available in Japan than in the U.S., but major Japanese space robotics programs and a diversity of smaller projects are supported.

Japanese Experimental Module

The Japanese Experimental Module (JEM) is Japan's contribution to the international Space Station Freedom project. JEM is a space laboratory for experiments in areas such as biology and crystal growth. When deployed, JEM will have a pressurized module for researchers, an exposed facility for experiments, and a remote manipulator system (RMS) to service experiments and maintain the exposed facility. JEM's exposed facility portion is designed to be robot-friendly, eliminating the need for astronauts to perform routine maintenance and repair functions. The JEM/RMS has a large arm and small fine arm (SFA). The large arm is designed to conduct overall assembly tasks and to transport the SFA; the SFA provides dexterity. JEM's pressurized module includes an interior workstation for teleoperating the JEM manipulators using a single joystick.

JEM's large arm is mounted on the pressurized module just above the airlock and had 7 degrees of freedom (DOF). The manipulator is 9.7 m long and has a mass of 370 kg. It will maneuver a payload massing up to 7000 kg. Two cameras mounted on the arm permit the operator at the workstation to view large arm actions. A standard grappling mechanism is mounted on the end of the large arm to dock with tools, payloads, or the SFA.

The SFA relies on the large arm for transport, positioning, and stabilization. The SFA includes an interface with the large arm, an electronics module, camera assembly, manipulator, and end effector. This arm is 1.6 m long, has 6 DOF, and features a 3-DOF wrist. The SFA can move up to 10 cm/sec with a payload of up to 300 kg. A stereo camera mounted at the base of the manipulator displays images on a video monitor at the workstation.

In addition to the RMS, the Japanese have conceived the active compliance effector (ACE), which is designed to be mounted on the end of the JEM/RMS arm. ACE provides small motions that could be useful in compensating for inaccuracies of the

large arm. ACE was particularly interesting to the panel because the U.S. was planning nothing like it for its long-reach space manipulation.

Orbital Operations

Japan has identified orbiting space structures as a means to conduct space activities in the future. In addition to the Space Station Freedom, the Japanese envision their own robotic space laboratory, the Cosmo-Lab, and one corporation hopes one day to operate an orbiting space hotel. To realize these scenarios, the Japanese foresee free-flying robots that grab, dock, and manipulate while in orbit. Fixed-base systems, such as those appended to shuttles or stations, have many limitations.

The Japanese are developing a free-flying manipulator with satellite capture capabilities. Named the Autonomous Satellite Retrieval EXperiment (ASREX), it is a scientifically motivated, special-purpose experimental robot for retrieving satellites. A key technology required for the ASREX is coupled control of the free-flying vehicle and manipulator. Movement of the manipulator will cause a reactive movement of the satellite, which must be compensated for by position and attitude control. The Japanese plan to accomplish satellite capture autonomously using feedback from laser radar, which is being developed specifically for this project. In addition to the ASREX, the Japanese are planning the ETS-7, an ASREX-like device that would be controlled by a combination of autonomy and teleoperation and would be capable of rendezvous and docking operations.

Japan's Space Flyer Unit (SFU) is a reusable satellite bus with onboard infrastructure, such as power, telemetry, and control, which could host free-floating experiments. Scheduled to fly in the early 1990s, it was justified independent of its relevance to space robotics, though it would enable scientific robotic experiments.

Japanese assembly and service robot concepts were still in the early planning stages at the time of the panel's visit. The Orbital Service Vehicle (OSV) is envisioned as a free-flying extra-vehicular activity (EVA) robot for inspecting, assessing, and repairing satellites or space structures. It will include thrusters, a manipulator, visual sensors, laser radar, a high-gain antenna, and a docking mechanism. *Hope* is envisioned as an unmanned shuttle-type vehicle. Its long-reach manipulator will transfer cargo, capture satellites, and aid in space assembly. As of 1990, the first launch was planned for the mid-1990s.

Surface Exploration and Construction

The Japanese are envisioning missions to the moon and to Mars, and speculate on the use of robots for surface exploration. Extreme conditions on other planets, including heat and cold, radiation, and rough terrain, require robots that are mobile; have competent motion in hard or soft terrain; remain upright or are self-righting; and that are physically self-contained, durable, and autonomous. In May 1990, the

Japanese announced a three-part lunar survey mission projected for launch in 2000. The unmanned Lunar Mobile Explorer (LME) is planned to investigate soil characteristics, collect samples, and confirm the presence or absence of water under the moon's permanent shadow.

The Japanese are also conducting research and development in mobile robots for nonspace applications. They have developed several wheeled, tracked, and hybrid mobile robots. They have also conducted research on legged robots that were candidates for space applications. Although the Japanese have had no experience in developing and testing mobile robots on planetary surfaces, they have a wealth of experience in terrestrial analogs, particularly in nuclear and construction applications. This will be a clear advantage for future surface operations.

Supporting Technologies

The Japanese are performing basic research for future generations of robots. The panel encountered a spectrum of supporting technology, including task control, motion control, master-slave systems, novel mechanisms, actuators and devices, and special-purpose robot integrations. Task control technologies were advancing Japanese manipulation from teleoperation toward autonomy. The panel observed outstanding Japanese motion control technologies: position and force control, hybrid control, use of digital signal processors to successfully increase the response and stability of control systems, and miniaturized actuators and components.

One notable system uses a series of head-mounted video displays to drive a slave video camera. This system includes a master-manipulator, slave-manipulator, and real-time graphic simulator. Human movements, including head and eyeball movements, are measured in real time. The movements of the robot sensors are controlled to follow the human operator, and images taken by the robot sensors are displayed to the human operator's eyes. Other notable Japanese master-slave systems include a 6-DOF bilateral teleoperator with a kinematically dissimilar master and slave, a master-slave manipulation system with visual and force feedback, and teleoperators enabling dynamic manipulation.

Japanese robotics researchers have developed a number of novel mechanisms, actuators, and devices, including manipulators, serpentine mechanisms, and high-performance miniature actuators and controllers. One interesting flexible finger system is controlled by pneumatic servos. Each finger is a hollow rubber cylinder divided into three chambers that are pressurized independently. The fingers are moved by varying the pressure in the chambers. Each finger is capable of fine, controlled movement, e.g., threading a bolt into a plate.

Serpentine mechanisms have a great deal of potential for space applications because gravity loads do not apply. Such systems, morphologically and functionally

analogous to snakes, tentacles, or elephant trunks, are characterized by long reach, narrow profile, and the ability to conform to complex shapes.

The panel noted that the Japanese have excelled in developing focused, special-purpose systems, some of which could find applications in space: a ladder-climbing robot; a teleoperated live-line maintenance robot; an inspection robot for containment vessels; vacuum-compatible actuators and robots; bipedal walkers; a plant tissue culture robot that can select, grasp, cut, and transport seedlings; and a piano-playing robot that can read and play music.

Perspectives

Vision and planning, coupled with a strong robotics research infrastructure, are enabling the young Japanese space program to develop relevant systems for space. Many successful Japanese development programs involve a stair-step approach, or rapid prototyping of technology generations, rather than a continuous evolution or one-time technological leap. The typical Japanese approach to robotics system challenges has been, and will probably continue to be, to first develop and deploy a baseline capability. System improvements can then take the form of distinct incremental upgrades.

At the same time, the Japanese often display a minimalist approach to space robotics technology. In some of their robots, they use technology adequate to getting the job done, thus avoiding the major costs associated with concerns about future evolution. To a marked degree, the Japanese tend to incorporate special-purpose electronics and devices (digital signal processors, application-specific integrated circuits, very large-scale integration, and special-purpose actuators) into their robotics. Overall, Japanese robotics hardware is more notable than its associated software.

The panel concluded that the Japanese were significant participants in space robotics with everything necessary to succeed: the technology, experience, and commitment to reach their objective of competent space robots.